

Electrohydraulic Brake System - The First Approach to Brake-By-Wire Technology

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ABSTRACT

As new smart systems for passenger cars are assisting the driver to handle manoeuvres in critical and normal situations, brake systems are required to fulfill the compatibility and interface demands. These advanced brake systems will be operated in a remote mode during normal braking and for autonomous brake interventions. BOSCH is developing a brake-by-wire system on a hydraulic basis, called 'Electrohydraulic Brake EHB'. Brake pressure build-up is supplied by a high pressure accumulator. Generation of the high pressure is done by an electric motor driven pump, similar to current ABS-systems.

Pressure at the wheel brakes is individually controlled by closed-loop pressure control, consisting out of inlet, and outlet valves, pressure sensor and corresponding algorithm. It is specified, that this control must be completely noiseless, proportional, fast, and highly accurate. To raise the acceptance of such a system, it will be introduced with a conventional hydraulic backup. The backup actuates the front wheel brakes. In the normal operating mode the master cylinder is switched to a hydraulic pedal travel simulator to give the right feeling and sensitivity at the brake pedal.

The system comes together with ABS, ASR, and VDC functions, optimized by using the wheel brake cylinder pressure information and proportional brake pressure control. It incorporates electronic brake force distribution between front and rear and even left and right, thus improving stopping distances and stability, making better use of the rear brakes than conventional systems.

It can be shown that ABS and other regulations can be done fully hidden for the driver. No noise from the pressure control or pedal reactions are noticed.

Autonomous vehicle guiding systems, such as advanced cruise control, collision avoidance (assist) systems, necessary for Intelligent Vehicle Highway System IVHS, and functional upgrading like hill-holder systems, and parking aids will have an ideal brake basis to act on.

Further concepts of integrating various other drivetrain and comfort systems will have a brake system that fulfills their needs. Functional enhancement can be added to the brake system with minimal hydraulic modifications.

MARKET DEMAND

Current technology for passenger car brakes consists out of hydraulic actuated friction brakes. ABS is getting standard in most applications. Vacuum boost or in minor cases hydraulic boost is essential for easy brake operation. Development efforts on these systems concentrate on comfort and ease of use. The market hardly honors additional efforts to increase performances or decrease disturbances. Major steps demand costly hardware changes and additional parts. With electronic control getting cheaper and rising ability to incorporate complicated strategies conventional hardware seems to be at its limits. Where interaction with other smart systems is needed conventional brake system hardware has to be supplemented with additional components. ASR and VDC systems need extra valves and further measures to improve their performances at low temperatures. In some applications not just the hydraulic system is being upgraded, even the pneumatic boost will be electronically controlled with added electropneumatic valves and sensors. Vacuum energy derived from gasoline engine intakes is originally a low-cost power supply but getting more expensive. In Europe a high Diesel engine content makes engine adapted vacuum pumps necessary. There are some gasoline engines with separate vacuum pumps for the vacuum booster. The vacuum pressure supply gets more difficult to use if valve and cylinder shut-off and total engine shut-off penetrate the engine development, neither do electric driven vehicles supply cheap vacuum.

Autonomous guiding systems demand even high braking performance by computer controlled activation. With this being seen also the normal braking can be done by sensing the drivers command to decelerate the vehicle and then

letting the computer take control over the actual energy supply to the wheel brakes.

At this point it makes sense to reconsider the whole brake system and come up with a new idea of integrating amplification, modulation and energy generation for the brakes. Once this integration takes place into one system called electrohydraulic brake system additional benefits will be gained with respect to packaging, weight and system application.

Concentration in this paper is pointed solely to electrohydraulic rather than electromechanical systems. These dry brake systems sometimes called pure brake-by-wire systems are considered too, but out of present view their realization does not seem to appear in the near-by future. Basic physical restrictions concerning the power density of directly electrically operated systems seem to prefer hydraulic systems, at least as long as the vehicle power network stays as it is today. The current single circuit electrical system neither is suitable to fulfill the power demands nor the safety needs of such a system. With other future systems requesting higher voltage in the vehicles than 12 V new chances for direct electrical actuation of the brakes might arise.

The reliance just on electrical links between command and actuation still has some psychological hurdles to overcome. To raise the acceptance systems will be placed on the market first that still have a conventional backup, in which the driver can apply the brakes with his own foot force. These systems should also fit onto the standard wheel brake actuators and should not make special caliper design necessary. Ideally the actuation system would be uniform for all possible brake applications independent of the vehicle drive train concept, the vehicle weight or the size of the wheel brakes.

For fast pressure gradients in the brakes calipers with higher volume consumption need a remarkable volume flow, which could be easily provided out of a high pressure accumulator. Specifications for pressure gradients are about 1500 bar/s for pressure build up as well as for release.

The pure energy consideration also reduces the chances for electrohydraulic systems at which the brake actuation power is directly converted from electric to hydraulic during actuation. One might take pump or plunger systems into consideration here, which do not have the dynamic advantages that accumulator systems have. Besides the thought of the unsuitable power conversion from electric to hydraulic its transformation on demand normally is combined with noise, which is not acceptable. The noise is related to the power rather than to the energy conversion, preferring systems with hydraulic storage. In these systems the conversion can be done in reasonable times with low power, thus minimizing the electric motor and the pump size.

The concept of the electronic and hydraulic system design is shown in Figure 1.

EHB – Electro Hydraulic Brake

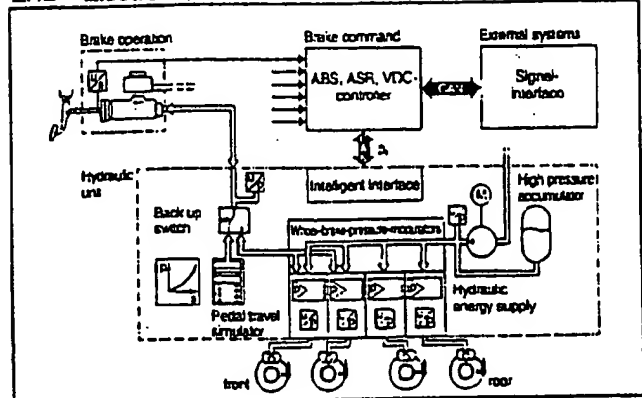


Figure 1: System schematic

DESCRIPTION OF THE HYDRAULIC SYSTEM

In conventional brake systems man-operated brake pressure build-up is silent besides some suction noise from the vacuum booster. So the benchmark for the pressure control is inaudibility. This is achieved by proportional governing of pressure build-up and decrease valves. But not just the pressure control also the energy for the brake operation has to be gained unnoticed. The high pressure pump is controlled from the ECU and revolution control of the electric motor gives variable pump power. Adjusting the pump power to the needs of the brake operation and to the environmental conditions serves to minimize acoustic disturbances. Special hydraulic means are also provided to dampen the piston type pump noise. The pump design is a carry-over from the next generation ABS return pump.

Central idea of the hydraulic layout of the system is the wheel individual brake pressure control. This control is active at any pressure build up or decrease. For normal partial braking as well as modulated pressure control by algorithms for slip control the proportional control is essential. Continuous control is well established in industrial hydraulic systems, e.g. using servovalves with internal position control. This valve type is far too expensive to be used in automotive applications. To reach the goals of accurate, silent, and proportional pressure control technology is derived from current two stage valves being used in standard ABS hydraulics (BOSCH ABS 5). These valves are operated with current control to be held in equilibrium stages during partial opening. Slight modifications in the valve design are made for the valve seat contours and magnet circuit design. The specifications for the proportional activated valves are slightly different from the fast switching two stage valves, where the target of switching time is replaced by hydraulic stability. The close relation to the switching valves keeps the valve costs for the EHB regulation valves close to mass production ABS valves. At this point the prerequisite to make the system marketable is given.

Having leak-proofed seat valves that are closed in the unfired position as a basic, pressure hold without energy consumption is a positive effect.

The complete closed loop pressure controller consists out of an inlet and an outlet valve, a pressure transducer mounted in the valve housing unit and the appropriate digital control algorithm in the microcontroller together with the current control power stages. There are four of these pressure modulators - one for each wheel brake. The development goal is to have robust control under all temperature and wear conditions that are occurring in the lifetime of the vehicle.

During normal straight braking set pressures at the two wheels of one axle are equal, a balance valve compensates the potential aberration of the two control circuits in the open position (see Figure 2). In all cases where the set pressures for left and right brakes are different the valve is energized to be closed. This is the case under braking and cornering or ABS regulation.

A switching device decouples the master cylinder from the brakes during normal EHB-operation and allows direct access of the master cylinder pressure to the wheel brakes in the backup mode. This mode is automatically active in case of power fail. In the EHB-mode the master cylinder pressure is fed into a device called pedal travel simulator, an elasticity which gives the wanted pedal feel similar to conventional systems. This simulator is a hydraulic cylinder with a spring loaded piston. The characteristics of the spring defines the pedal feel. A valve, which could be hydraulic-mechanically or electrically driven, decouples the pedal travel simulator in the backup mode.

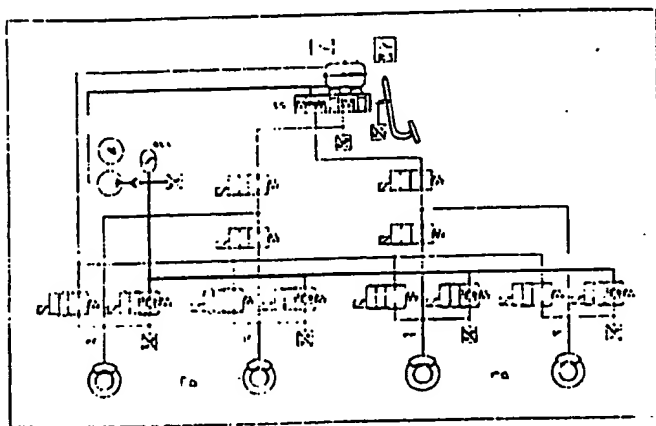


Figure 2: Hydraulic layout

The hydraulic energy is generated in a piston pump derived from an ABS return-pump. To achieve the required noise levels the pump is located directly at the accumulator, the pump outlet leading into the accumulator volume.

The accumulator is a membrane type high pressure accumulator with a specially developed sandwich type membrane to meet the specifications for diffusion and gas loss over the component life time. The sandwich type membrane incorporates a plastic layer with very fine pore diameter.

The size of the accumulator is designed to give sufficient volume to do three full brake applies after the pump has failed. The charge control is using the pressure signal from the accumulator pressure transducer. The pressure level is controlled to the needs of the brake locking pressure, which is permanently observed. With loss of brake efficiency respectively rising brake temperature the stored pressure level is raised from 150 up to 220 bars.

The pump power is modulated by pulse width control of the applied voltage. The necessary pump power is derived from calculating the hydraulic power consumption for brake apply using vehicle speed and engine revolutions to estimate the environmental condition and allowed noise level.

The communication with other systems is done via the CAN network.

Six pressure transducers are built into the hydraulic unit. Hydraulic and electric connections to the attached ECU are integral part of the sensor array design. The design volume of the built-in pressure transducers is kept to a minimum not having own housing, signal amplification, and connectors for each sensor. The transducer technology is determined by safety aspects like overload and bursting conditions, preferring a steel membrane type transducer with thick film strain gauges.

Pressure transducers, switching, and regulation valves, pump, and ECU are all integrated in the hydraulic unit with the accumulator attached. Its total volume is comparable to a standard ABS/ASR hydraulic unit. The size of the accumulator and eventually the pump motor are adaptable to the size of the wheel brakes.

PEDAL UNIT

The EHB pedal unit consists out of a standard tandem master cylinder with central valves. For ease of packaging the pedal travel sensor can be integrated into the master cylinder. Having a special design master cylinder the integration of the pedal travel simulator and switching valve is straight forward. The adaption of the flange and push rod of the master cylinder has to be done to be compatible to the normally used vacuum boost.

A different approach is to use a standard master cylinder and replace the booster by a unit that integrates the travel simulator, the mechanical switch off and the travel sensor.

The omission of the booster saves space behind the fire wall. Especially the vehicle design benefits with minor modifications for left and right hand drive and positive effect on the crash deformation near the driver's feet.

ELECTRONIC CONTROL UNIT CONCEPT

The basic control of wheel brake pressures is being computed in an attached ECU at the hydraulic unit. This is a microhybrid technology [1] built two microcontroller ECU. It serves for signal processing of the pressure transducer signals, processing the pressure control algorithm in a relatively small cycle time of some milliseconds, and governing the pulse-width modulated power stages. Both signal conditioning and power stage control have to be performed as close as possible to the components for EMI-reasons. The switching valves to lock the master cylinder in the EHB-mode and the balance valves are also controlled from this ECU. Besides the valve control accumulator pressure and pump control is also done here.

In the safety concept the stand-alone capability of this control unit for EHB-braking without additional functions is demanded. Additional functions as described later are calculated in a second control unit which in the first realization would be mounted remote. The communication between both ECUs runs via a serial data link using CAN protocols. Basically desired pressures are transmitted in the one direction and actual, measured pressures in the opposite direction. Additionally valve current information and other signals necessary for the remote part of the safety software are transmitted, too. In the other direction some flags for the identification of the control state are transmitted. The structural concept for the two ECUs is hierarchical, the attached ECU is responsible for the basic pressure regulation functions to operate the brakes, the remote ECU handles all wheel and vehicle related functions like stability of the wheels, more sophisticated brake pressure proportioning, and total car behaviour together with the later explained coordination of the braking requests.

FUNCTIONALITIES

Brake pedal apply is characterized by a short stiff pedal feel. Full pedal travel is about 60 to 80 mm (24"-32"). The relation between pedal travel and pedal force can be chosen during the application of the system. It is then put into hardware as the layout of the pedal travel simulator springs. This characteristic of the pedal is independant of the volume consumption of the brake calipers. So any curve in the diagram (Figure 3) could be chosen. Such a new freedom in tuning the brake interface to the driver is been given by decoupling it from the brake actuation. A short, reactive feel seems to be preferred. Maximum used actuation forces are in the range of 200 N at the pedal, which is the maximum applied pedal force resulting from street driving tests [2], indicated grey in the diagram. Recent investigations in driving simulators also show that

these limits are often not exceeded even in emergency situations.

The relation between the pedal feel and the reaction of the vehicle gives the overall, subjective impression of the brake feel. The controller gets information about pedal travel and master cylinder pressure. The functional use of this measures is open to software tuning, giving the vehicle manufacturer or even the end consumer easy access to his own preferred taste. Both sensor informations, stroke and force can be used to determine the driver's wish to decelerate the car. Use of the derivatives of the sensor signals can be made to identify special circumstances.

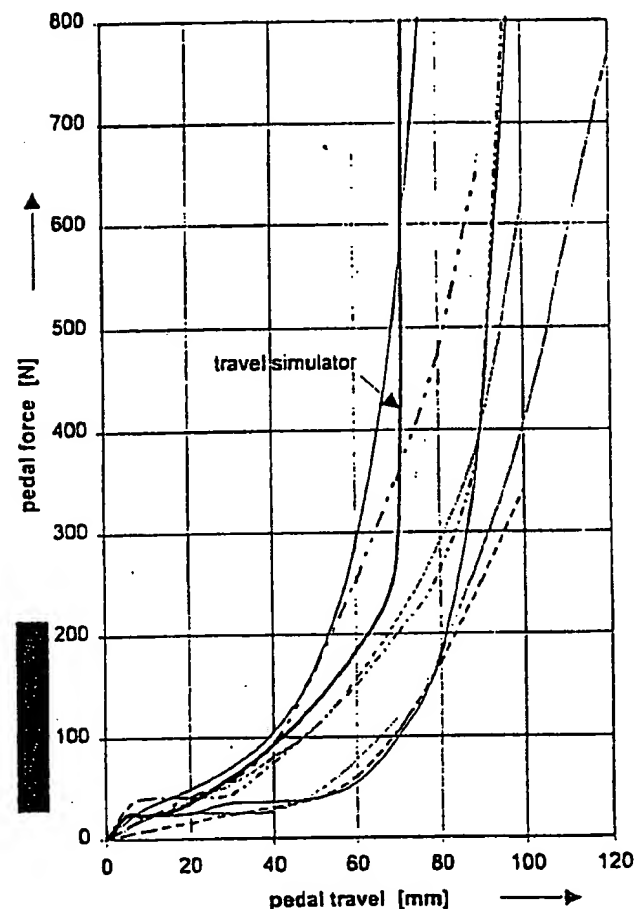


Figure 3: Measured brake pedal characteristics of European production vehicles [2] and proposed travel simulator characteristic, the grey bar indicates typical applied pedal force

Identification of fast brake apply leads to a modified relation of brake pedal actuation to deceleration of the vehicle. This so-called panic-brake strategy can use further information of fast accelerator pedal release or in a more advanced stage can use information from a distance sensor combined with adaptive cruise control systems [3]. Versus fixed amplification of a conventional brake system, as indicated by a solid line (Figure 4) a whole field of

amplification is open for use under different circumstances and manufacturer's taste. The upper limit of the amplification is given by the maximum allowable pressure and the dosability applying the pedal. Even locking pressure of the wheels can easily be reached under high thermal load of the brakes when fading occurs respectively. is compensated.

The pedal travel signal is more sensitive for the first movement of the pedal even in the dead travel zone before the master cylinder valves close, whereas the master cylinder pressure information is better related to the feeling at further pushed brake pedal. Out of safety reasons each information at its own must be sufficient to give satisfactory deceleration. The redundancy of the information is also used for safety checks and offset compensation using the brake-light switch signal as the third information about brake pedal actuation.

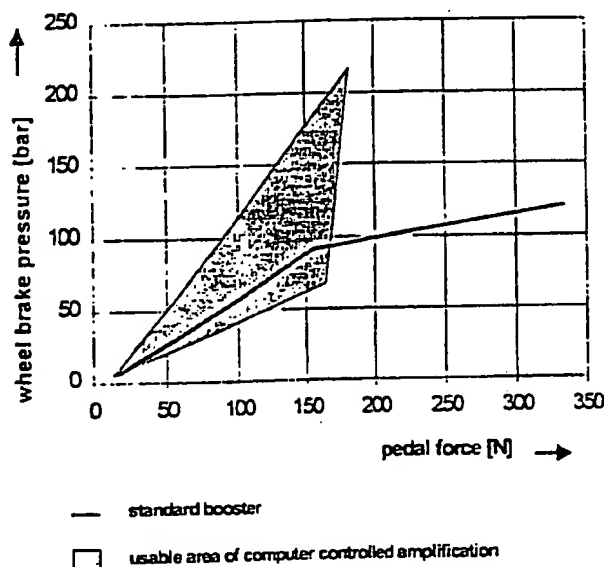


Figure 4: Range of boost function

The driver's command can be interpreted in most cases as a desired deceleration. Thus a deceleration controller is responsible for the determination of the total braking force of the vehicle. The actual wheel brake pressures are then calculated in a brake force distribution module. This uses various information about vehicle speed, wheel slip, lateral acceleration, estimated vehicle weight, weight distribution, estimated tire normal forces, and estimated brake temperature to determine the four wheel brake pressures. Brake force distribution for standard straight braking is calculated from ideal, parabolic, dynamic weight distribution between front and rear axle. The center of gravity coordinates and the deceleration determine the shift from static weight distribution. Other influences like aerodynamic longitudinal and vertical forces dependant on the vehicle speed can be added to the computation of tire normal forces and needed brake pressure. The brake

moment can be proportionally adjusted to the tire normal forces, giving relatively more moments to the front to be on the safe side of stability.

During braking and cornering lateral acceleration leads to extra weight distribution from the curve inside to the outside wheels.

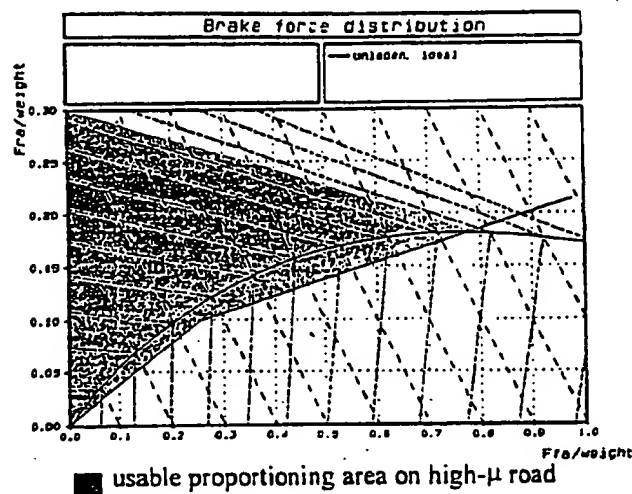


Figure 5: Brake force proportioning

This dynamical behaviour is calculated in a vehicle model that uses the lateral accelerometer signal. Brake moment distribution according to the transferable friction forces can lead to more stable behaviour of the vehicle still before a detected mismatch between the driver's intended course and actual vehicle course leads to a VDC-system interaction [4, 5].

In a further development this VDC interaction is not any more orientated at threshold bands but can be continuously used to control the steering behaviour of the vehicle by taking or giving side forces from or to the individual wheels. The EHB-system is especially well suited to do so because of its imperceptible action.

For low deceleration the rear axle might be used more than according to the weight distribution. The additionally usable area in the front/rear distribution diagram is shown in Figure 5. The addition is referred to conventional brake force distribution with proportioning valves. Potential instability on low- μ surfaces is inhibited by observing the actual rear wheel slip and then reacting on increasing slip by proportioning more brake force to the front at defined deceleration.

Advantages of distributing more brake force to the rear are a better subjective drag feel during braking, less dive of the vehicle, and more equal brake pad wear between front and rear. Proportioning the brake force also means distributing the heat sources for the dissipation of the kinetic energy. And this allows to introduce cooling phases during long time steady braking going long passes downhill. Peak temperatures of the front brakes can be reduced. In

principal these tests define the brake size, and a chance here is to reduce it.

The deceleration controller can also take other braking systems into account. Engine drag can be used or compensated which is especially interesting for electric motor applications where the recuperative power determines the usable drag moment. Only electronic brake control can distribute the vehicle braking power to different systems without the driver noticing.

The quality of the deceleration control can be enhanced if an additional signal for the longitudinal acceleration of the vehicle can be provided. Situations when the brake apply is not directly related to a desired deceleration can then be identified, this might be the case going downhill where brake apply just serves to keep the vehicle speed constant. Longitudinal acceleration could be gained from suspension systems or an additional sensing axis could be added to the VDC-system lateral accelerometer.

SLIP CONTROL

In case of using the tire-road friction to its limits the pressure at which the wheel tends to lock or is getting instable is known. This pressure level is closely related to the maximum friction coefficient. Together with the brake efficiency observer a kind of friction sensing is realized. New chances and enhanced performances for the ABS or ASR algorithms arise [6]. Pressure build-up after release can easily be done close to the known maximum allowed pressure. Knowing the friction coefficients at all for wheels at a time gives straight information about special conditions like split- μ or rough roads. These can be reacted on faster and securer than under estimation as today. Specific strategy adaption to the derived conditions enhances the system performance.

Observing the brake efficiency the brake pressure levels can be used to compute the deceleration of the vehicle, having a basis to calculate the vehicle reference speed. With the accuracy of the vehicle speed better slip control is given, allowing the slip controller to act more precise. Best use of the maximum tire-road friction at last leads to shortest stopping distances.

Besides sensing the friction coefficient the proportional pressure control depending on the wheel behaviour gives smooth braking force changes. The slip control offers a very comfortable performance without deceleration variations on homogeneous surfaces. Together with its inaudible and pedal reaction free actuation it can be made totally imperceptible for the driver. If needed the slip control can be indicated in the dashboard or by a loudspeaker.

Of course the system enters the market as a high performance, top level system with best available vehicle control features. The VDC-system of BOSCH [4] went into production a year ago representing the safest dynamic control of the vehicle. The EHB system serves as the

underlayered hydraulic system to get maximum control quality out of the VDC-algorithms. This means the complete system will be offered with all sensors needed for dynamic vehicle control. These are steering wheel angle sensor, yaw rate sensor, lateral acceleration sensor, and optional longitudinal acceleration sensor.

Basic sensors and switches are active wheel speed sensors, brake light switch, and fluid level switch. The locations of the sensor packaging are shown in figure 6. In a complete system integration concept sensors and interactions of other systems are used to determine and influence the dynamic behaviour of the vehicle.

For building up an enhanced network with other systems a powerful bus system like the CAN bus is mandatory, making engine control, gearbox control accessible and giving access to advanced vehicle guiding systems. Also dashboard control via CAN is recommended.

EHB – Electro Hydraulic Brake

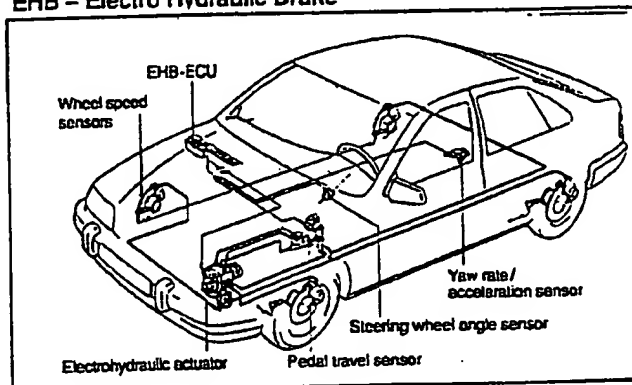


Figure 6: System packaging

ADDITIONAL FUNCTIONALITIES

Wheel individual active brake pressure can be utilized for a number of innovative features. One of the easiest functions to implement is the hill-holder function. Knowing the wheel brake pressure it is straight forward to implement the hill-holder function. Depending on the system specifications operating times of up to half an hour are requested. The electric energy consumption is minimal. Safety considerations with respect to pressure loss in the brakes and resulting loss of the hold function are not an issue. The EHB-system could detect potential pressure loss and can rebuild the determined pressure, besides giving warnings to the vehicle operator.

Fading of the brakes can be compensated to a reasonable level. The efficiency of the brakes is permanently observed and up to a certain loss of efficiency an overlayed deceleration controller can raise the pressure level for a desired deceleration with rising temperature. The limits for the compensation are where the driver should be informed

about the deteriorating brake condition. Same is true for wet brakes or otherwise affected braking power.

At this point a look at future friction pairing like carbon-carbon is interesting. What makes these materials unsuitable for current applications is their bad cold temperature efficiency. Pressure gain dependant on the efficiency of the wheel brakes but comes with EHB making the use of this kind of materials feasible. Provided their costs get controlled a considerable weight reduction could be achieved.

SYSTEM PERFORMANCE

Recent investigations on drivers reactions to emergency situations seem to show that the advantages of ABS are not fully used in practice. European as well as NHTSA publications prove statistically the benefits of ABS but they also claim an increasing accident rate under special conditions. An explanation is searched in the drivers behaviour to the uncommon situation. In vehicle simulators a percentage of untrained drivers tends to release braking pressure in emergency cases despite necessity for full braking power. The training level of the car users is dependant on the country and their own education in managing the critical driving situations. Efforts are taken to enhance this level by offering publications and courses to the public. In Europe ABS-braking is sometimes also included in normal driving school lessons. The fundamental ABS safety feature of remaining steerability during full brake apply can be used fully if the situation has been trained before.

In some investigations drivers did not reach the braking force to get maximum deceleration of the vehicle. Both indications give arguments to design a system like EHB, where the amplification and modulation of the brake pressure is decoupled from the driver. In critical situations the driver is not diverted by uncommon pedal reactions and can concentrate on avoiding the obstacle. He reaches maximum braking performance with low pedal forces. As a conclusion the EHB-system is better suited to cope with low driving experience, which is regarded as a further safety margin.

At braking commands from other systems the pedal feel remains the same as under normal conditions. Other systems that might want to communicate to the EHB-system are autonomous intelligent cruise controls with RADAR distance control or just parking aids with ultrasonic distance control. In the farer future collision avoidance systems with video picture processing or traffic sign reading systems all have the means to interfere in the brake system. The EHB offers a standard interface to do so. Special coordination algorithms then have to decide which request would be fulfilled. These algorithms have to take the vehicle driving condition into account. A VDC system is essential to decide about the brake interference. Basic coordination is already implemented in the current BOSCH

VDC systems on the market, that handle engine, gearbox and brake intervention. For each new system that wants to make use of the active braking capability the coordination performance has to be extended.

SAFETY CONCEPT

The hydraulic design schematic of the system incorporates the fundamental ideas with respect to safety and reliability of the overall concept. In case of a detected failure in a system component the safety algorithms decide whether to shut off the electronic control totally or to further operate the electrohydraulic brake system under a degraded mode together with appropriate warning of the driver.

Degraded modes are in general used as long as the braking performance is higher than in the hydraulic back-up mode. E.g. a loss of one pressure control circuit, meaning one wheel cannot be braked, still gives better stopping in the electronically controlled mode with three wheels than the unamplified back-up mode on all four wheels. In this case the driver would hardly realize that a severe failure has occurred, at least not during normal braking. Therefore together with the failure indication in the dashboard braking can be made uncomfortable depending on the severity of the detected failure. The relation between pedal effort and deceleration can be disadjusted or even the deceleration can be made unsteady. Thus the car holder would be informed about the system condition to have his vehicle serviced.

If the algorithms cannot cope with the failure the last back-up would be mechanically hydraulic with the electronic system been shut off, this mode has to be automatically generated at a power shut-off. The uncontrolled backup mode has at least to fulfill the legal regulations in terms of pedal effort to gained deceleration of the vehicle.

These legal demands are easily covered with a single one axle backup-circuit. But for the first introduction of the system one would enhance the performance of the back-up mode by supplying pressure to both the front and rear axle. Thus gaining approximately 0.6 g with 500 N pedal force depending on the parameters of the vehicle. Hybrid backup meaning conventional on one axle, electronically controlled on the other axle is not considered to be useful, also for the sake of complexity of the safety algorithms.

Safety algorithms feature plausibility checks of the sensor information versus each other and versus models that are permanently calculated in parallel to the control of the system. These include an accumulator charge model, where pump time and valve operation time and gained wheel pressure are compared to the accumulator pressure information. It uses fundamental gas laws as a physical basis.

Same is done at the closed loop pressure control circuits, where valve operation time, control stability and wheel speed information serves for a wheel brake model to be compared to the actual brake pressure information.

Besides these models there is also a model running to observe the redundant information of pedal travel and master cylinder pressure. An offset of these parallel sensor read-outs could eventually be interpreted as gas (air) contamination of the backup circuit. In this case the availability of the backup is reduced and a driver warning has to be given.

The accumulator supplied controlled system is hardly affected by gas-contaminated brake fluid, but a deteriorated backup capability makes a service necessary and is comparable to a circuit loss in a conventional system. In this case the primary performance would not be reduced. Gas detection ability is essential for the safety of the system.

Critical failure conditions would be given if a single failure both destroyed the EHB system as well as the backup. This single failure could be an accumulator membrane rupture that is not detected before the backup lines are spoiled by gas bubbles. Means against the occurrence of this situation are a reliable, fast gas detection in the high pressure storage system, a backup design that can cope with a substantial amount of gas in it, still fulfilling the legal regulations, a low probability of a membrane rupture by safe design and endurance testing. The gas detection algorithms are under development and a more expensive alternative with a piston type gas accumulator is still under investigations.

To make use of all the available sensor information during the system initialisation a pre-drive-check is run after power on. This power on is not simultaneous with ignition on, but system initialization has to be done with door actuation, e.g. central lock signal. This is to ensure the braking performance to be ready before the driver can move the vehicle and not to lose time before the gearbox clearance can be given. During the pre-drive-check wheel brake pressure will be build up and cross information of hydraulically connected pressure sensors will be gained. The pre-drive-check also has to check the accumulator pressure sensor information, during the stand-still of the vehicle wheel brakes and accumulator can be hydraulically connected to compare the wheel brake pressure sensor information with the accumulator pressure sensor. Offset compensation can be calculated then. Offset calculation of all other sensors can be calculated during normal unbraked operation.

With the multiple sensor information the whole brake system can be diagnosed during operation. Leakage, loss of brake efficiency, caliper failure, brake fluid condition, or eventually brake disc wobble can be identified and warnings can be given even before the failure is severe enough to cause trouble. The failure trace can be stored and service is simplified.

The development of the whole safety concept is made much easier by the use of a powerful simulation based on the development of earlier systems [7].

SUMMARY

Market demand for a new active brake system is taken seriously. An electrohydraulic brake system EHB is based on available valve technology. For dynamic reasons a high pressure accumulator serves as a hydraulic buffer. Application to existing wheel brake design is straight forward. Packaging, weight, volume, and performance advantages are expected from significant technical innovation. The expensive development of such a new system requires a reasonable production volume to be profitable. This can be achieved if costs of the system meet the conventional baseline and if functionally upgraded systems are requested by the customers.

Development of comfort and safety functions of the brake system are separated from the hydraulic system design. This opens a wide field of tunable and newly realizable functional upgrades. Easy integration into system networks is provided.

The system is expected to raise the acceptance of brake-by-wire concepts to prepare the market for the next major step to dry, purely electrical systems. The electrohydraulic solution has the prospect of earlier realization in this century.

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